Improvements in Navigation Resulting from the Use of Dual Spacecraft Radiometric Data

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When two interplanetary spacecraft lie along similar geocentric lines-of-sight, navigational advantages may be achieved by navigating one spacecraft with respect to the other. Opportunities to employ this technique will become more common as more multiprobe missions are launched. The two Viking spacecraft and the two Mariner Jupiter/Saturn '77 spacecraft will be within two and three degrees of each other, respectively, for a large portion of their missions. Results of simulated analysis as well as the processing of real tracking data from the two Viking spacecraft reveal the following advantages of the dual spacecraft navigation technique: (1) cancellation of platform parameter and transmission media modeling errors in short arc solutions, (2) accurate encounter guidance for the trailing spacecraft, (3) reduction of total tracking requirements, and (4) rapid determination of the orbit following a maneuver on either spacecraft.

I. Introduction

Many of the interplanetary missions which are likely to take place during this and the next decade involve two spacecraft. For example, both the Viking and MJS '77 missions have two spacecraft that often approach to within a few degrees of each other in the sky. For a couple of years it has been conjectured that navigational capabilities (at least for the trailing spacecraft) might be substantially improved if the radiometric data from the two spacecraft were not treated independently but somehow combined. The rationale for this is based primarily on the following two observations:

(1) Once the leading spacecraft has flown by or gone into orbit about a planet, its orbit with respect to the planet is known to within a few km.

(2) If the leading spacecraft is used as a beacon for the trailing spacecraft many of the common error sources such as ephemeris errors, transmission media, and station location errors should cancel.

When the two spacecraft are tracked simultaneously from neighboring ground sites, the common error sources may be removed by differencing the corresponding data types from the two spacecraft. The information retained by the new data types will include the differences in right ascension and declination between the two spacecraft as well as the difference in geocentric range rate (differenced doppler data) or the difference in geocentric range (differenced range data). Under certain conditions, relatively error-free determinations of these quantities should improve navigational capabilities. Results of this study obtained from real radiometric data demonstrations show that dual spacecraft data types can improve navigation capabilities by a factor of 5 to 10 under the conditions of small angular separation between spacecraft and a well determined reference spacecraft.

A couple of years ago some introductory work on dual spacecraft tracking was performed at the Jet Propulsion Laboratory (JPL) (Ref. 1). Results of that study indicate the potential advantages of the concept. Recently we have completed a fairly thorough accuracy analysis study of dual spacecraft tracking using simulated tracking data based on the trajectories of Viking and MJS '77 missions. These results, which are to be described in this paper, are extremely encouraging. For instance, the Viking B navigational errors can be reduced by an order of magnitude. It has been found that in addition to the cancellation of common errors dual spacecraft tracking can reduce the tracking time requirement and help the low declination problem.

Of course before this technique can be incorporated routinely in mission design (e.g., MJS) it is necessary to obtain sufficient tracking experience and demonstrate that the expected improvement in navigation can actually be achieved. Hopefully, the necessary data to conduct such a demonstration will be made available during the Viking mission. Results of dual spacecraft tracking conducted during the early cruise phase of Viking mission are included in this paper.

II. Information Content of Single Spacecraft Single Station Radiometric Data

Before proceeding into a discussion of the new data types of dual spacecraft tracking, it will be worthwhile to briefly review the information provided by single-station, single-spacecraft radiometric data. The range, ρ, and range rate, $\dot{\rho}$, from a tracking station to a spacecraft can be approximately given by the Hamilton and Melbourne model (Ref. 2).

$$\rho = at - b \cos \omega t + c \sin \omega t + d$$

$$\dot{\rho} = a + \omega b \sin \omega t + \omega c \cos \omega t$$

where

$a = \dot{r}$ = geocentric range rate at $t = 0$

$b = r_s \cos \delta$

$c = \omega t_\epsilon r_s \cos \delta$

$d = r - z_s \sin \delta$

and

r = geocentric range of spacecraft at $t = 0$

δ = declination of spacecraft

r_s = distance of tracking station from Earth's spin axis

z_s = distance of tracking station from Earth's equator

ω = Earth's rotation rate

t = time past meridian crossing

t_ϵ = Error in time past meridian crossing

The slowly varying geocentric term, r and $\dot{r}$, provide acceleration information, and the sinusoidal modulation, b and c, produced during each tracking pass by the spin of the earth yields geometric information on the right ascension, α, and the declination, δ, of the spacecraft. The above equations provide insight into several of the limitations of single-station, single-spacecraft range and doppler data for determining the spacecraft state. The limiting factors may be summarized as follows:

(1) Low declination singularity,

(2) Station location errors (including variations in earth spin rate-UT1-and polar motion).

(3) Transmission media effects (space plasma, atmosphere).

(4) Ephemeris errors,

(5) Unmodelled spacecraft accelerations.

(6) Tracking station availability.

Part of the above limitations may be examined from the following relations derived in Ref. 2.

$$\sigma_\alpha^2 = \frac{\sigma_c^2}{(r_s \cos \delta)^2} + \omega^2 \sigma_{UTI}^2 + \sigma_\lambda^2$$

$$\sigma_\delta^2 = \frac{\sigma_b^2}{(r_s \sin \delta)^2} + \frac{\cos^2 \delta}{(r_s \sin \delta)^2} \sigma_{r_s}^2$$

From the first equation, the errors in *UT1* (i.e., earth spin rate) and station longitude, λ, directly limit the accuracy of the determination of right ascension. The second equation shows the poor determination of declination at low declination and the effect from station location errors in r_s. The transmission media effects degrade the α, δ accuracy through the parameters, b and c.

The effect of unmodelled spacecraft accelerations is not included in our simplified equation for $\dot{\rho}$. However, it is clear that such accelerations add a spurious signature which, if of significant magnitude relative to ωb and ωc, can severely degrade the determination of both α and δ.

In recent years a program has been undertaken at JPL to develop new data types and estimation techniques (Ref. 3) to alleviate some of the problems discussed here. For example, simultaneous differenced doppler will remove unmodelled spacecraft accelerations; high precision simultaneous range will remedy the low declination problem, and S/X-band dual frequency doppler can be used to calibrate charged particle effects. For outer planet fly-by missions the primary limitation of conventional radiometric navigation is ephemeris uncertainties. As discussed in Ref. 3, the most promising method of reducing ephemeris problems involves the use of onboard optical data. The onboard optical data, though promising, is considered less reliable than radiometric data. For two spacecraft missions the dual spacecraft tracking has been found to be another way to reduce the effects of ephemeris uncertainties using radiometric data. In principle, the first spacecraft may be used as a beacon to guide the second spacecraft. If the two spacecraft have a small angular separation, many of the error sources will be common and will cancel. In the next two sections, we will show, through this simple model, that the dual spacecraft tracking is also insensitive to station location errors, the low declination singularity and transmission media effects.

III. Dual Spacecraft Two-Station Data

If the two spacecraft are being simultaneously tracked by two nearby ground stations, we call it dual spacecraft two-station tracking. The range and range rate to a second spacecraft (subscript 0) whose orbit is well determined and used as a beacon may be written as

$$\rho_0 = r_0 + \dot{r}_0 t_0 - r_s \cos\delta_0 \cos\omega t_0 + \omega t_{\epsilon 0} r_s \cos\delta_0 \sin\omega t_0 - z_s \sin\delta_0$$

$$\dot{\rho}_0 = \dot{r}_0 + \omega r_s \cos\delta_0 \sin\omega t_0 + \omega t_{\epsilon 0}\, \omega r_s \cos\delta_0 \cos\omega t_0$$

Where, as in Ref. 1, for mathematical simplicity the tracking station associated with the second spacecraft has been assumed to be collocated with the tracking station associated with the first spacecraft. These simultaneous range and range rate data may be differenced to form a new set of data types: dual-spacecraft two-station range and range rate. Taking the expansion with the following quantities

$$\Delta\alpha = \alpha - \alpha_0$$

$$\Delta\delta = \delta - \delta_0$$

$$\Delta r = r - r_0$$

$$\Delta\dot{r} = \dot{r} - \dot{r}_0$$

and neglecting second-order terms in $\Delta\alpha$, $\Delta\delta$, the new data type may be represented as

$$\rho - \rho_0 = \Delta r + (\dot{r}t - \dot{r}_0 t_0) - \Delta\delta z_s \cos\delta_0 + b_2 \cos\omega t_0 + c_2 \sin\omega t_0$$

$$\dot{\rho} - \dot{\rho}_0 = \Delta\dot{r} - \omega b_2 \sin\omega t_0 + \omega c_2 \cos\omega t_0$$

where

$$b_2 = r_s \Delta\delta \sin\delta_0$$

$$c_2 = r_s \Delta\alpha \cos\delta_0$$

From the above relations the differential quantities $\Delta\alpha$ and $\Delta\delta$ can be more accurately determined, since

$$\sigma^2_{\Delta\alpha} = \frac{\sigma^2_{c_2}}{(r_s \cos\delta_0)^2} + \frac{\Delta\alpha^2}{r_s^2}\sigma^2_{r_s} + \Delta\alpha^2 \tan^2\delta_0\, \sigma^2_{\delta_0}$$

$$\sigma^2_{\Delta\delta} = \frac{\sigma^2_{b_2}}{(r_s \sin\delta_0)^2} + \frac{\Delta\delta^2}{r_s^2}\sigma^2_{r_s} + \frac{\Delta\delta^2}{\tan^2\delta_0}\sigma^2_{\delta_0}$$

The right ascension difference $\Delta\alpha$ is no longer affected by the common errors due to *UT1* and station longitude. The small value of $\Delta\alpha$ effectively reduces the sensitivity to errors in r_s and δ_0 as shown in the first of the above two equations. The low declination problem is also solved to a large extent as shown in the second equation. The most important evidence is that the error in $\Delta\delta$ due to r_s is nearly removed since the second term is now multiplied by the small quantity $\Delta\delta$ instead of being magnified by the inverse of $\sin\delta$ as in single-spacecraft tracking. This small difference of declination also makes the last term in the second equation well behaved at low declination. The sensitivity to low declination now exists only in the first term, the observed parameter, which may be improved by increasing observations. Furthermore, for the same amount of data, the parameter b_2 should be more accurately determined than the corresponding parameter b because of the better data quality of dual spacecraft tracking due to the cancellation of the atmospheric effects.

It is interesting to have an estimate about how well the atmospheric effects cancel for small angular separations. Figures 1 and 2 show the sensitivity to errors in the calibration for tropospheric refraction (a 10% or 20-cm error is assumed at the zenith). For angular separation less than 5 degrees, the 10% error is almost an order of magnitude less important in the dual-spacecraft range and doppler than in the conventional single-spacecraft data types. The presence of unmodelled accelerations from both spacecraft limits us to the use of either the sequential estimation technique (permitting the inclusion of process noise compensation) or the dual spacecraft four-station data types (so-called ΔQVLBI) which will be discussed next.

IV. Dual Spacecraft Four-Station (ΔQVLBI) Data

If the same spacecraft is simultaneously tracked from two widely separated tracking stations such as Goldstone and Australia, differencing of the corresponding data types from the two stations provides differenced range and doppler (sometimes called QVLBI range and doppler as in Ref. 2) that are free of geocentric range and range rate terms and hence relatively uncorrupted by unmodelled spacecraft accelerations. With dual-spacecraft tracking these differenced range and doppler data from both spacecraft will again be differenced. These twice-differenced new data types require the simultaneous tracking at four stations, and thus they are called the dual-spacecraft four-station data types. The differenced range and range rate observables from a single spacecraft may be written in terms of the line segment (baseline) between stations as follows

$$D\rho = z_b \sin\delta + r_b \cos\delta \sin\omega t_b - r_b \omega t_\epsilon \cos\delta \cos\omega t_b + \Delta t$$

$$D\dot{\rho} = \omega r_b \cos\delta \cos\omega t_b + \omega r_b\, \omega t_\epsilon \cos\delta \sin\omega t_b + \Delta f$$

where

r_b = baseline projection on equatorial plane

z_b = baseline component in the spin axis direction

λ_b = longitude of the perpendicular to r_b

Δt = error due to station clock bias

Δf = error due to station frequency bias

After performing the similar expansion and differencing, the dual spacecraft four-station (ΔQVLBI) data types may be given as

$$D\rho - D\rho_0 = z_b \Delta\delta \cos\delta_0 + b_4 \cos\omega t_{b_0} - c_4 \sin\omega t_{b_0}$$

$$D\dot{\rho} - D\dot{\rho}_0 = \omega b_4 \sin\omega t_{b_0} - \omega c_4 \cos\omega t_{b_0}$$

where

$$b_4 = r_b\, \Delta\delta \cos\delta_0$$

$$c_4 = r_b\, \Delta\delta \sin\delta_0$$

Notice that in addition to the removal of unmodelled accelerations the errors due to station clocks are not present in the above equations of four-station data types. This is due to the fact that those collocated stations are either conjoint stations which share a common station clock or the clock bias and drift can be accurately determined by short baseline data (Ref. 4). These new data types are relatively clean because of the double differencing and reduce the number of parameters to three in range observables and two in range rate observables. The uncertainties of the determination of $\Delta\alpha$ and $\Delta\delta$ may be estimated as before by

$$\sigma^2_{\Delta\delta} = \frac{\sigma^2_{c_4}}{(r_b \sin\delta_0)^2} \left(\frac{\Delta\delta}{r_b}\right)^2 \sigma^2_{r_b} + \left(\frac{\Delta\delta}{\tan\delta_0}\right)^2 \sigma^2_{\delta_0}$$

$$\sigma^2_{\Delta\alpha} = \frac{\sigma^2_{b_4}}{(r_b \cos\delta_0)^2} + \left(\frac{\Delta\alpha}{r_b}\right)^2 \sigma^2_{r_b} + (\Delta\alpha \tan\delta_0)^2 \sigma^2_{\delta_0}$$

The sensitivities to the parameters b_4, c_4, r_b and δ_0 are the same as for the dual spacecraft two-station data types discussed in the previous section. Figure 3 shows the uncertainties of the angular position, α and δ, of the spacecraft determined from one pass of dual spacecraft doppler data. The angular position error of the reference spacecraft is independent of that of the other spacecraft and is assumed to be $\sigma_{\delta_0} = \sigma_{\alpha_0} = 1 \times 10^{-7}$ rad.

We used the relation

$$\sigma_\alpha^2 = \sigma_{\Delta\alpha}^2 + \sigma_{\alpha_0}^2$$

$$\sigma_\delta = \sigma_{\Delta\delta}^2 + \sigma_{\delta_0}^2$$

to compute the results shown in Figure 3. Data noise is assumed to be 0.2 mm/s (0.003 Hz) at 60-s integration time and $\sigma_{r_s} = \sigma_{r_b} = 1.5$ meter. It is interesting to learn that the right ascension can be determined to within 0.04-arc second compared with a 0.15-arc second accuracy from conventional data due to a 3-meter error in longitude. The declination uncertainty increases as declination decreases, and at low declination the uncertainty increases with the angular separation $\Delta\alpha$ and $\Delta\delta$. When δ_0 is 2 degrees the declination error is about 0.20 arc second as a result of dual-spacecraft, two-station tracking. The corresponding error from conventional single-spacecraft tracking is as large as 1.7 arc seconds due to the low declination problem. The results of this simple analysis clearly reveal the potential capabilities of dual-spacecraft tracking. Results of simulated analysis as well as the processing of real tracking data from the two Viking spacecraft will be discussed next.

V. An Algorithm for Processing Dual Spacecraft Data

Before we go to the discussion of the results of orbit determination (OD) based on dual-spacecraft tracking, it is worthwhile to explain the algorithm used in our analysis. Ideally speaking, the particular OD program for studying this problem should be able to handle the twelve-parameter state vector of the two spacecraft. It would have been a major effort to implement such an OD program; instead we designed and developed a special program to difference the data files obtained from the OD runs made for each spacecraft separately. After that the new data types of dual-spacecraft tracking are created with partial derivatives for the reference spacecraft included. This new data file is then ready for OD analysis.

In the OD analysis of the dual-spacecraft tracking, the covariance of the six-state parameters of the reference spacecraft which is already in orbit about or has flown-by a planet will be generated from an OD run fitting the fly-by or orbit data. Then the covariance which gives the best estimate of the state of the reference spacecraft relative to the planet will be used as a priori values for the reference spacecraft in the orbit determination of the second spacecraft. When we use dual-spacecraft, two-station data, the unmodelled accelerations from the second spacecraft are estimated sequentially. The unmodelled accelerations from the reference spacecraft which are not dynamic parameters to the second spacecraft are also estimated sequentially treating them as a random noise such as that due to the transmission media. The six-state parameters of the reference spacecraft are not estimated, but their errors are *considered* (i.e., their effect on the accuracy of the solution is taken into account). We believe that this is a valid way to process the dual-spacecraft data and study the information content of the new data types.

VI. Results of Simulated Analysis

A. The Viking Spacecraft

1. **Data.** Each of the three DSN (Deep Space Network) complexes has three tracking stations, i.e., stations 11, 12, 14 at Goldstone, California, 42, 43, 44 at Canberra, Australia, and 61, 62, 63 at Madrid, Spain. Thus continuous coverage of simultaneous tracking of two spacecraft is possible. In the analysis it was assumed that Viking A was tracked by stations 12, 42, and 62 and Viking B was tracked by stations, 14, 43, and 63. Doppler data was continuous and two-way range points were taken about every 3 hours. Because Viking B suffers from low declination problems nearly simultaneous range points between California and Australia were also included every day for both spacecraft. To include the information provided by the Viking A data into the solution for Viking B, two new data types, dual-spacecraft differenced doppler ($\Delta\dot{\rho}$) and differenced range ($\Delta\rho$) are formed by simply subtracting the Viking B doppler/range from the Viking A doppler/range.

2. **Estimated and considered parameters.** The navigation solutions solved for the state of Viking B and considered the effects of errors in station locations[1] (Δr_s = 1.5 m, $\Delta\lambda$ = 3.0 m, Δz = 15 m), constant nongravitational accelerations (1.2×10^{-12} km/s^2), ephemeris of Viking A orbit (2 km at periapsis), ephemeris of Mars ($\approx$ 30 km), and several of the primary harmonics of Mars. When the data is differenced almost all of the geocentric range, and range rate information cancels. Therefore, when differenced data is used a small amount of loosely weighted single station/single spacecraft doppler and range data will be included to retrieve the geo-

[1]The station location parameters of the two stations at the same site are highly correlated in the OD solutions so that their relative errors are small (10 cm).

centric range and range rate information without significantly degrading the declination and right ascension information.

3. Results for dual-spacecraft two-station data ($\Delta\rho$, $\Delta\dot{\rho}$). The first solutions used two-station differenced doppler and range. As expected, the degrading effects of the station location errors on the B-plane[2] solutions were reduced by an order of magnitude from similar errors resulting from the use of conventional single-spacecraft data. Unfortunately, the few km errors in the ephemeris of the Viking A orbiter produced errors in the B plane solution for Viking B which were thousands of km. This result was also expected because an error of a few km in the orbit of the orbiter will introduce 10^{-8} km/s^2 unmodelled acceleration errors into the dual-spacecraft data. It is well known that if the data of an interplanetary spacecraft is subject to unmodelled accelerations of this size, the navigation solutions will be in error by thousands of km.

4. Results for dual-spacecraft four-station data (ΔQVLBI). It has been shown that one method of reducing the effects of large unmodelled accelerations is to take data from one spacecraft simultaneously from two widely separated stations and then subtract the first station's data from the second station's data. This type of data is commonly called QVLBI data. Based upon our experience with single spacecraft, QVLBI data, we thought that if Viking A is tracked simultaneously from two stations, (e.g., 12 and 42) and at the same time Viking B is tracked simultaneously from two other stations (e.g., 14 and 43) going through a double differencing between both the spacecraft and the stations a new data type will be generated which will be insensitive to both unmodelled acceleration errors and to station location errors. We chose to call this new data type ΔQVLBI and it does improve navigation capabilities by an order of magnitude. One of the major error sources in QVLBI doppler data is the frequency bias between the two-way and three-way data. The effect of this error source should also be substantially reduced in the ΔQVLBI data.

5. Comparison between single- and dual-spacecraft navigation. A comparison of navigational capabilities resulting from the use of single-spacecraft data with those resulting from the use of dual-spacecraft (ΔQVLBI) data is shown in Figure 4 for 10-day and 20-day data arcs. The single-spacecraft data set consists of continuous three-station doppler (1 mm/s) and nearly simultaneous range (5 m). The first dual-spacecraft data set consists of ΔQVLBI doppler (1 mm/s) during the station overlaps and single-spacecraft, three-station nearly simultaneous range (5 m). This hybrid data set is included because it may be difficult to obtain ΔQVLBI range from Viking. The second set of dual-spacecraft data consists of ΔQVLBI doppler (1 mm/s) and QVLBI range (1 m) during the overlaps. The ΔQVLBI range is weighted more tightly than the nearly simultaneous range because in the double differencing procedure many of the components of the range error will cancel.

Figure 4 clearly shows the improvement in navigational capabilities resulting from the use of dual spacecraft data. As mentioned earlier, the dual spacecraft four-station data type improves the navigational capabilities of Viking B by anywhere from a factor of five to an order of magnitude over that associated with conventional data. Furthermore, the dual spacecraft data should require less total tracking time and reduce the need for station location and transmission media calibration.

In the cruise phase of the two Viking spacecraft, another simulation study was performed tying the short arc trajectory of Viking A immediately after its maneuver to the long arc of Viking B. An accurate rapid redetermination of a spacecraft orbit following a midcourse maneuver is very important for a successful planet encounter. In this analysis we assumed a midcourse maneuver of the A spacecraft at 40 days before it encountered Mars. At that time the B spacecraft had a long arc and its orbit was well determined. Based on 4 days data after the maneuver, the target errors from the conventional data were as large as 1500 km mostly due to station location errors. By performing dual spacecraft tracking (two-station doppler and range) and tying the A spacecraft to the B spacecraft, this error was reduced to 300 km with more than one third of the error due to the uncertainty of the B spacecraft's orbit. From Fig. 5 we see again a factor of 5 improvement. About 4 weeks later Viking A had a long arc and the target error based on conventional data was brought down to 200 km. This comparison indicates that the 4-day arc solution based on dual-spacecraft tracking is nearly as good as the 30-day long arc single-spacecraft solution, and it shows the potential reduction of DSN tracking time requirements. Due to the limited ground tracking facilities and the long flight time associated with many deep space missions in the future, the tracking time limitation will be a serious problem.

B. The MJS Uranus Option Mission

In 1976 the MJS mission was redesigned to include an option to target the second spacecraft for Uranus after its Saturn encounter. This situation is made to order for a dual spacecraft strategy for the following reasons:

(1) The Uranus option for the second spacecraft will not be implemented unless a successful Saturn encounter is achieved by the lead spacecraft. Thus, the assumption that the first spacecraft will be available as a reference for the Uranus-targeted spacecraft is valid.

[2] The "B-plane" is JPL terminology for the target plane or aim plane. See Ref. 3 for the defining geometry.

(2) The Uranus option trajectory design stretches propellant reserves to the limit. A precise Saturn encounter by the second spacecraft will reduce the magnitude of the post-Saturn maneuver and increase the probability of having sufficient propellant for a successful Uranus encounter. In fact, if a large injection error or other propellant-wasting event should occur, the dual spacecraft strategy might be a means of preserving the Uranus option.

We have conducted a series of simulated analyses of dual spacecraft two-station and four-station data types for the MJS Uranus option in the same manner as the Viking simulation.

1. **Data.** The data distribution and arc length of the conventional data types for the second spacecraft are the same as used by MJS navigation analysts (Ref. 5). The data which consist of doppler and nearly simultaneous range from DSN stations 14, 43, and 63 start at 60 days before Saturn encounter. The data distribution is rather sparse in the first 30 days, but continuous in the second 30 days. For dual spacecraft tracking analysis, we generated the same data pattern at the same time interval for the first spacecraft that has already flown by Saturn and is 9 months ahead of the second spacecraft. In this analysis only the doppler from the two spacecraft are differenced to form dual-spacecraft two-station and four-station doppler. Due to the ground tracking capability and long round-trip-light time (longer than 2 hours) it will not be possible to have four-station simultaneous two-spacecraft range data. Therefore, we did not simulate any differenced range data.

2. **Estimated and considered parameters.** The estimated parameters are the state of second MJS spacecraft and the constant part of the unmodelled spacecraft accelerations. In the meantime the parameters of unmodelled accelerations from both spacecraft are estimated sequentially with a two-day batch size and a one-day correlation time. The assumed a priori for these accelerations is 10^{-12} km/s^2. The considered parameters are station location uncertainties (σ_{r_s} = 1.5 m, σ_λ = 3 m, σ_z = 15 m), range bias at each station (4.37 m), and the ephemeris of the reference spacecraft (~ 300 km Saturn relative). The ephemeris of Saturn is not considered since the spacecraft is tied to the planet through the fly-by of the first spacecraft which contains the ephemeris information of the planet.

3. **Results for dual-spacecraft two-station data ($\Delta\dot{\rho}$).** The differenced dual spacecraft doppler is weighted at 15 mHz (1 mm/s) at 60-s integration time, and the conventional doppler is loosely weighted at 150 mHz to retain the geocentric range rate information without degrading the planet relative information. The near simultaneous range data was weighted at 10 meters in our initial attempt because of the low declination problem ($\delta \approx 2$ deg). Later we found that the tight geocentric range data increased the sensitivity to the error of the ephemeris of the reference spacecraft by a factor of 6 and thus caused the B-plane uncertainty to be unreasonably large. Once we deweight the range to 1 km, the B-plane error as shown in Fig. 6 at six days before Saturn encounter becomes less than 600 km, which is less than half the error using conventional data types.

4. **Results for dual-spacecraft four-station data (ΔQVLBI).** As discussed earlier the dual-spacecraft four-station doppler is not sensitive to unmodelled spacecraft accelerations. Therefore, only the constant part of the accelerations from the second spacecraft are estimated together with the state of that spacecraft. The same parameters considered in the two-station data solutions are considered here. The four-station (ΔQVLBI) doppler is weighted at 7 mHz (0.5 mm/s) because of its better data quality after double differencing. The conventional doppler and range are weighted at 150 mHz (10 mm/s) and 1 km as the previous case. With this clean data type of four-station doppler, the target (B-plane) error based on the same data arc is reduced down to only 360 km, nearly 4 times better than that of the conventional data (Fig. 6). The promising results of this simulated analysis for the MJS mission show that even under a rather unfavorable situation, i.e., low declination and large angular separation ($\Delta\alpha \approx 9$ deg), the navigation accuracy can still be improved by a factor of 2 to 4 by performing dual-spacecraft tracking. It also gives us the confidence to demonstrate this new technique with real tracking data. Next we will show a couple of examples of demonstrations conducted during the cruise phase of the Viking mission.

VII. Results of Real Tracking Data Demonstration (Viking Cruise Phase)

A. Rapid Redetermination of Viking B

We processed 4 days of dual spacecraft two-station doppler data immediately after the first maneuver of the Viking B spacecraft early in September, 1975. Viking A at that time had a long arc solution of about 40 days and was used as the reference spacecraft. The doppler data with 60-s count time received at six DSN stations located at three different complexes (California, Spain, and Australia) were first compressed to a 10-min count time using a modified JPL data editing program. This program provides simultaneous compressed doppler data from the two spacecraft during concurrent tracking. During that time, the two spacecraft were not far away from Earth and thus station location errors were not important. So we purposely introduced large errors in station locations (Δr_s = 15 m, $\Delta\lambda$ = 20 m) to magnify the effects due to such errors. As shown in Fig. 7, the introduced station location errors moved the B-plane solution based on conventional data by as much as 10,000 km. While the dual-spacecraft two-station doppler with loosely weighted conventional data gave a solution only 1000 km away from the current best estimate. The results of this real data demonstration did indicate that short arc dual-spacecraft tracking is insensitive to station location errors.

B. A Low Declination Example

During late November of 1975, Viking B spacecraft was at a very low declination of about −2 deg. A total of seven days of dual spacecraft two-station doppler were processed. The dual-spacecraft data was weighted at 15 mHz and the conventional doppler and range loosely weighted at 150 mHz and 1 km, respectively. The resulting B-plane solution differed by only 600 km from the current best estimate. A large part of the 600-km error is believed to be due to the uncertainty from the reference spacecraft, Viking A. The conventional data with the same data arc and doppler weighted at 15 mHz and range at 1 km moved the B-plane solution by as much as 920 km mainly due to the low declination difficulty. Thus this example shows the navigation capability of the dual spacecraft tracking at an unfavorably low declination.

VIII. Concluding Remarks

As a result of this analysis, we may conclude the following:

(1) Dual-spacecraft data types, which are relatively insensitive to platform parameter errors, transmission media effects, low declination problems, and ephemeris errors, may improve navigational capabilities by a factor of 5 to a factor of 10, under the conditions of small angular separation ($\leqslant$ 3 degrees of the two spacecraft) and well determined trajectory of the reference spacecraft.

(2) Dual-spacecraft tracking has the potential of significantly reducing DSN tracking time requirements.

While our results, so far, are very encouraging, the work is not yet complete. We need to develop software enchancements to be able to apply sequential filtering simultaneously to both spacecraft and we need to perform more realistic demonstrations using real tracking data, such as Viking encounter data. The increased understanding and more thorough evaluation gained will be necessary before the dual-spacecraft tracking technique can be used in interplanetary navigation.

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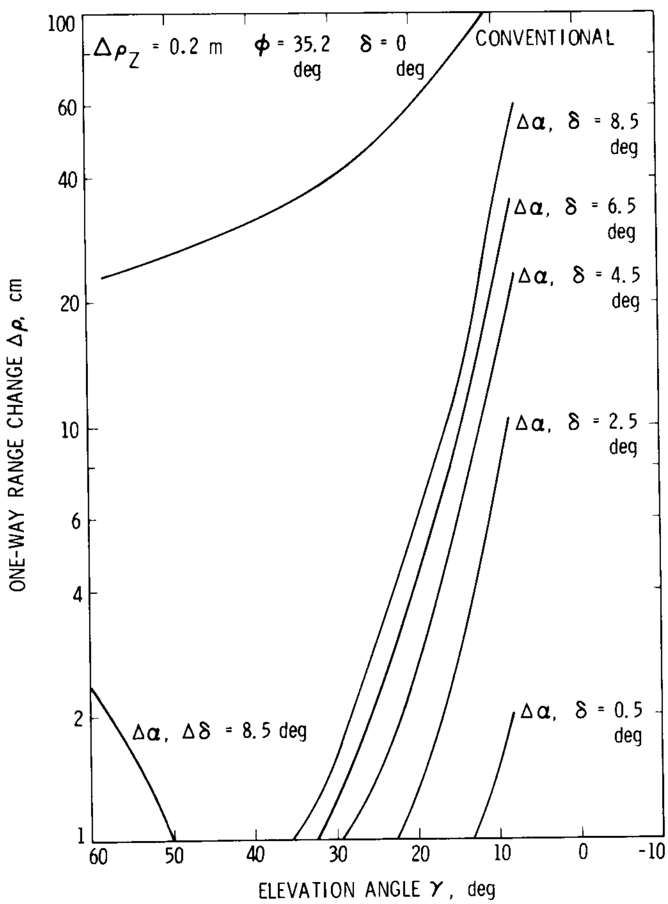

Fig. 1. Range change due to a 10% tropospheric effect

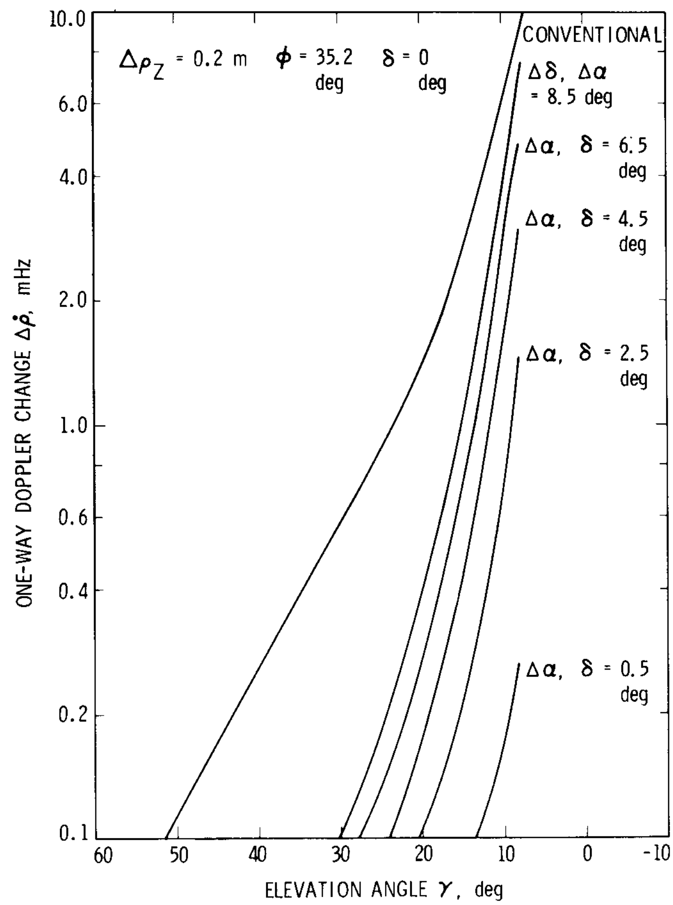

Fig. 2. Doppler change due to a 10% tropospheric effect

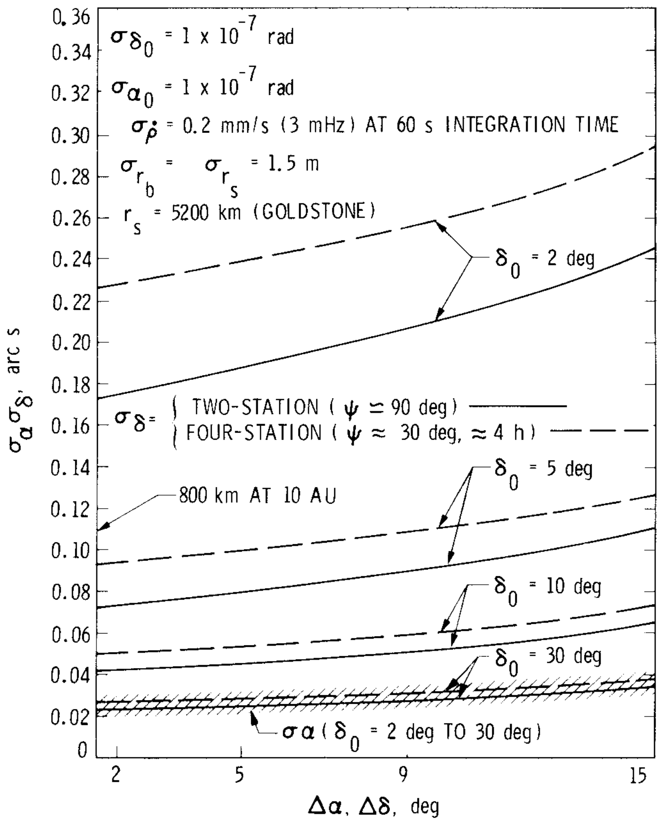

Fig. 3. Information content from a single pass of dual spacecraft doppler

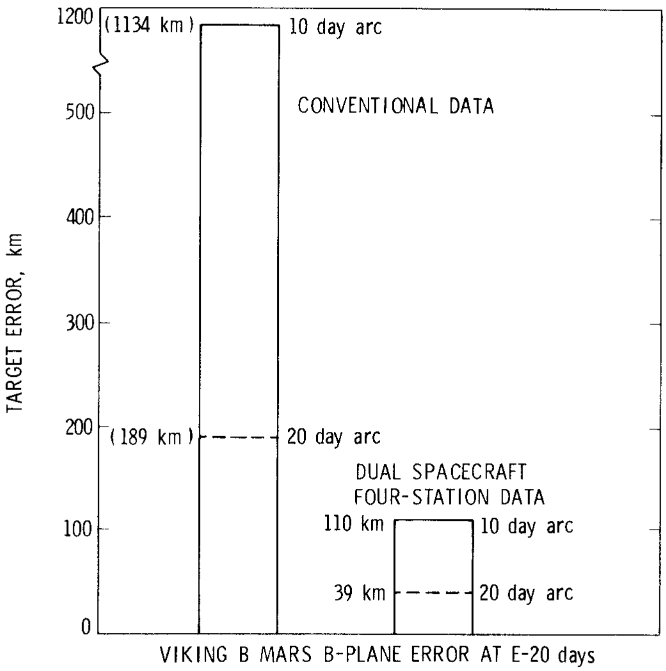

Fig. 4. Using Orbiter as a beacon

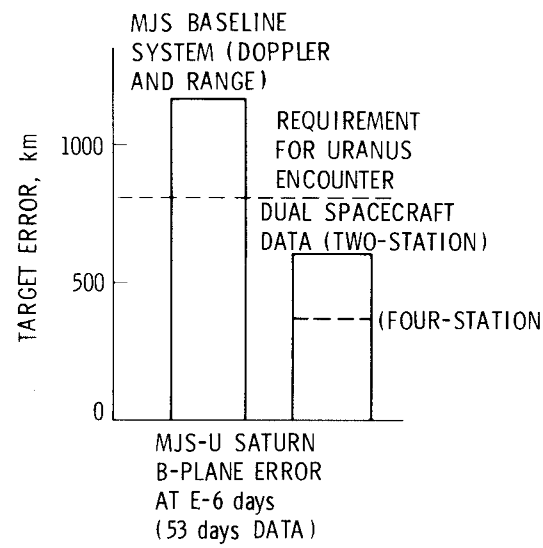

Fig. 6. Using fly-by spacecraft as a beacon

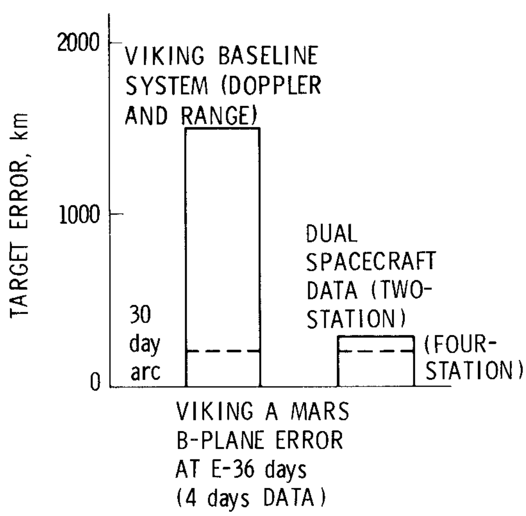

Fig. 5. Rapid determination of Viking A

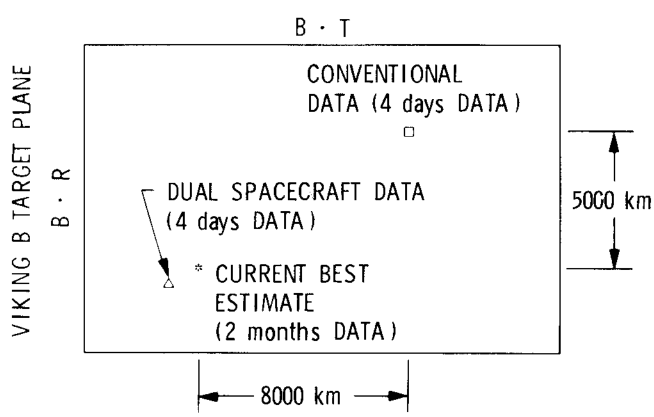

Fig. 7. Viking B target plane predictions using 4 days data with introduced errors in station locations (Δr_s = 15 m, $\Delta\lambda$ = 20 m)